Phase-field simulation of interactive mixed-mode fracture tests on cement mortar with full-field displacement boundary conditions

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Motivation

Phase-field modeling is an elegant approach to simulate complicated fracture processes, including crack initiation, propagation, merging and branching in a unified framework without the need for ad-hoc criteria and on a fixed mesh. The objective of this work is to provide qualitative and quantitative comparisons between interactive mixed-mode fracture test results in cement mortar and numerical simulations through phase-field approach.

Phase-field modeling of fracture

For brittle materials, the fracture problem is formulated as the minimization problem of the regularized energy functional [1]

$$\mathcal{E}_l(\boldsymbol{\varepsilon}, s) = \int_\Omega \psi_{\mathrm{el}}(\boldsymbol{\varepsilon}, s)\,\mathrm{d}\Omega + G_c \int_\Omega \left[\frac{1}{4\ell}(1-s)^2 + \ell\,|\nabla s|^2\right]\mathrm{d}\Omega,$$

where s is the phase-field parameter which describes the state of the material and varies smoothly between 1 (intact) and 0 (completely broken) and G_c is the fracture energy. Here ℓ is a length-scale parameter characterizing the width of the diffusive approximation of a discrete crack.

Governing equations

$$\operatorname{div}\boldsymbol{\sigma}(\boldsymbol{\varepsilon}, s) = 0$$

$$\boldsymbol{\sigma}(\boldsymbol{\varepsilon}, s) = g(s)\frac{\partial \psi^+_{\mathrm{el}}(\boldsymbol{\varepsilon})}{\partial \boldsymbol{\varepsilon}} + \frac{\partial \psi^-_{\mathrm{el}}(\boldsymbol{\varepsilon})}{\partial \boldsymbol{\varepsilon}}$$

$$2\ell\Delta s + \frac{1-s}{2\ell} = \frac{g'(s)}{G_c}\mathcal{H}^+$$

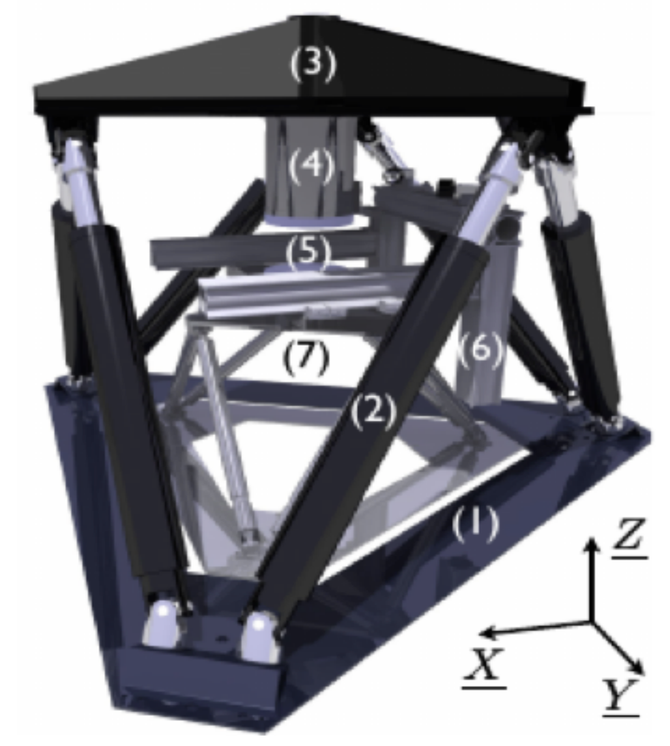
$$\mathcal{H}^+(\boldsymbol{x}) := \max_{\tau\in[0,t]}\psi^+_{el}(\boldsymbol{\varepsilon}(\boldsymbol{x},\tau))$$

Boundary conditions

$$\begin{cases} \boldsymbol{u} = \bar{\boldsymbol{u}} \text{ on } \partial\Omega_{\bar{u}} \\ \boldsymbol{\sigma}\cdot\boldsymbol{n} = \bar{\boldsymbol{t}} \text{ on } \partial\Omega_{\bar{t}} \\ \nabla s\cdot\boldsymbol{n} = 0 \text{ on } \partial\Omega \end{cases}$$

Experimental set-up

The testing machine can apply a complete twist(3 translations +3 rotations), wrench (3 moments+ 3 forces) or a combination of both to the boundary of the specimen.



Digital image correlation (DIC) can not only provide the full displacement field on each face of the sample as boundary conditions (BCs) for simulations, but also lead to the interactive adjustment of the applied BCs for generating more complex and stable crack patterns.

Fig. 1: Experimental set-up [2].

Comparison between experimental and numerical results

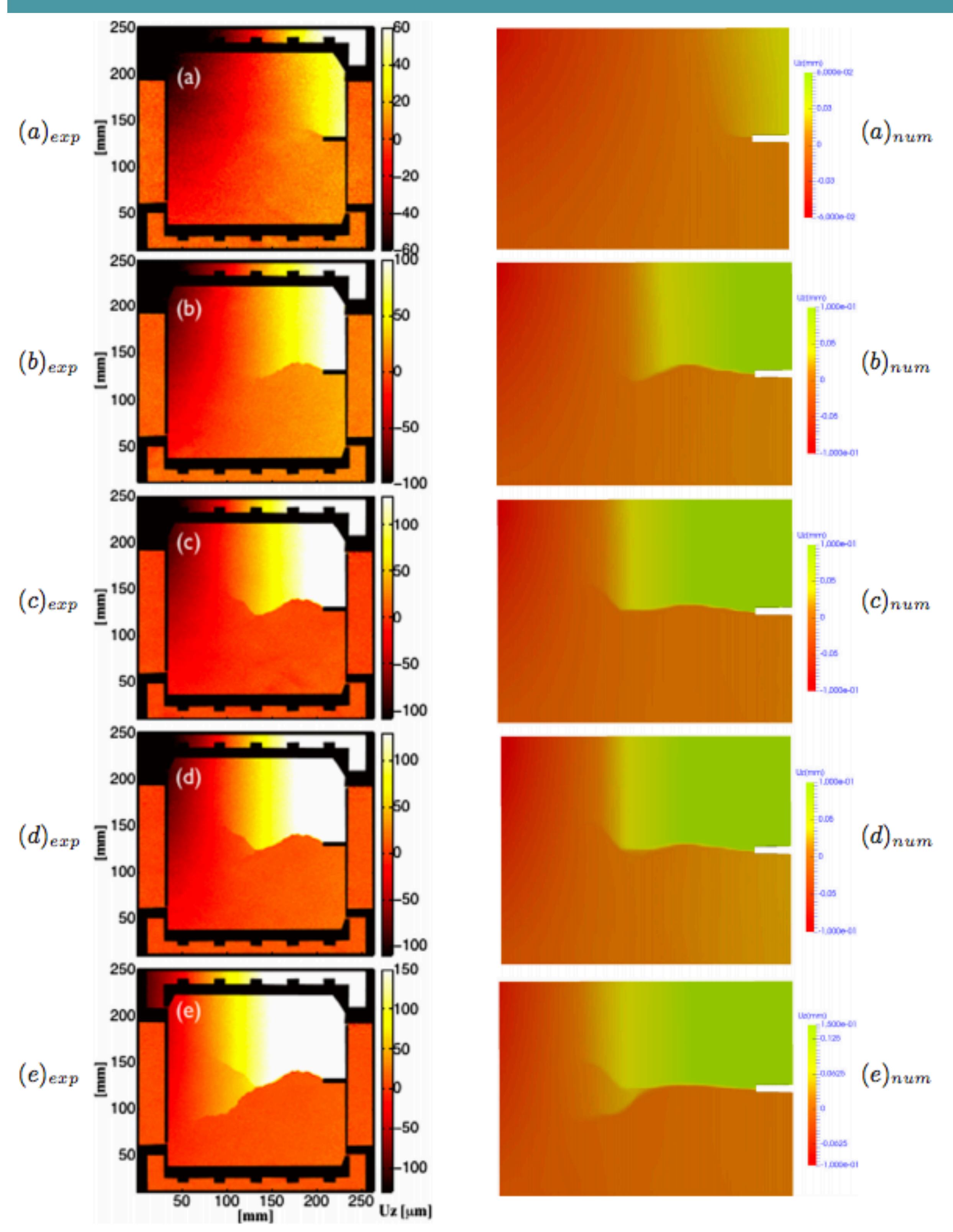


Fig. 2: Displacement contours (Z-component) on one face of the specimen (left) experimental data and (right) numerical results [3].

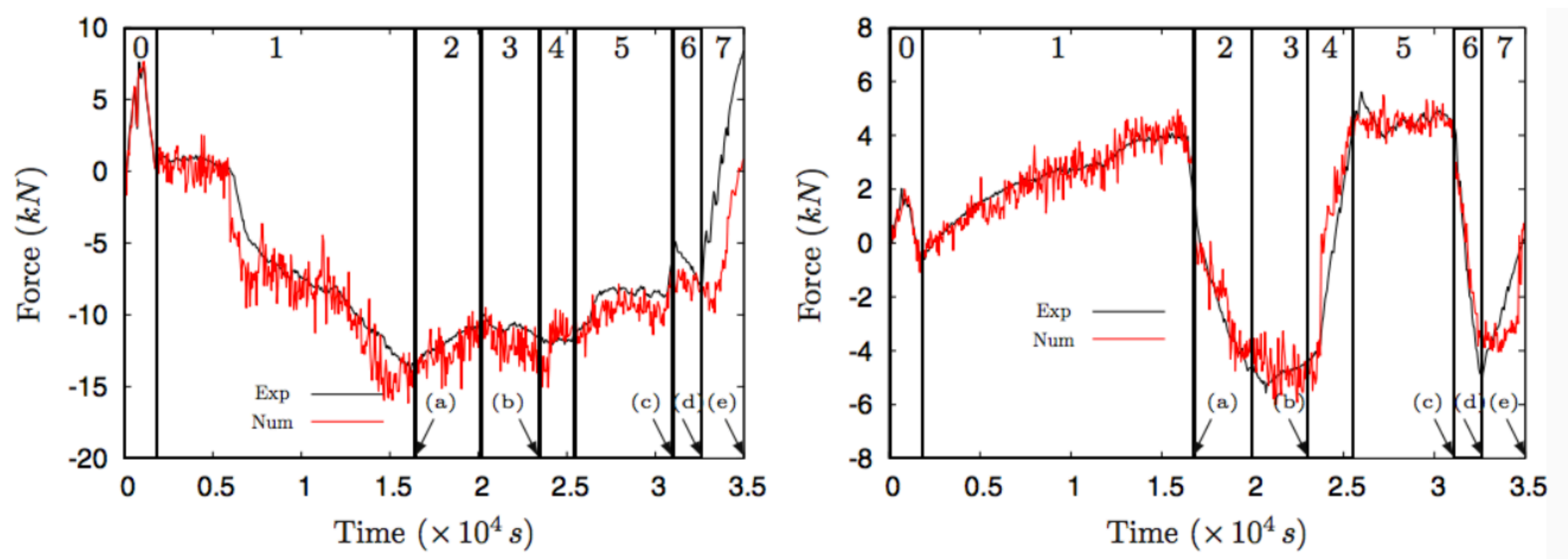


Fig. 3: Comparison between experimental and numerical results for (left) normal force and (right) shear force.

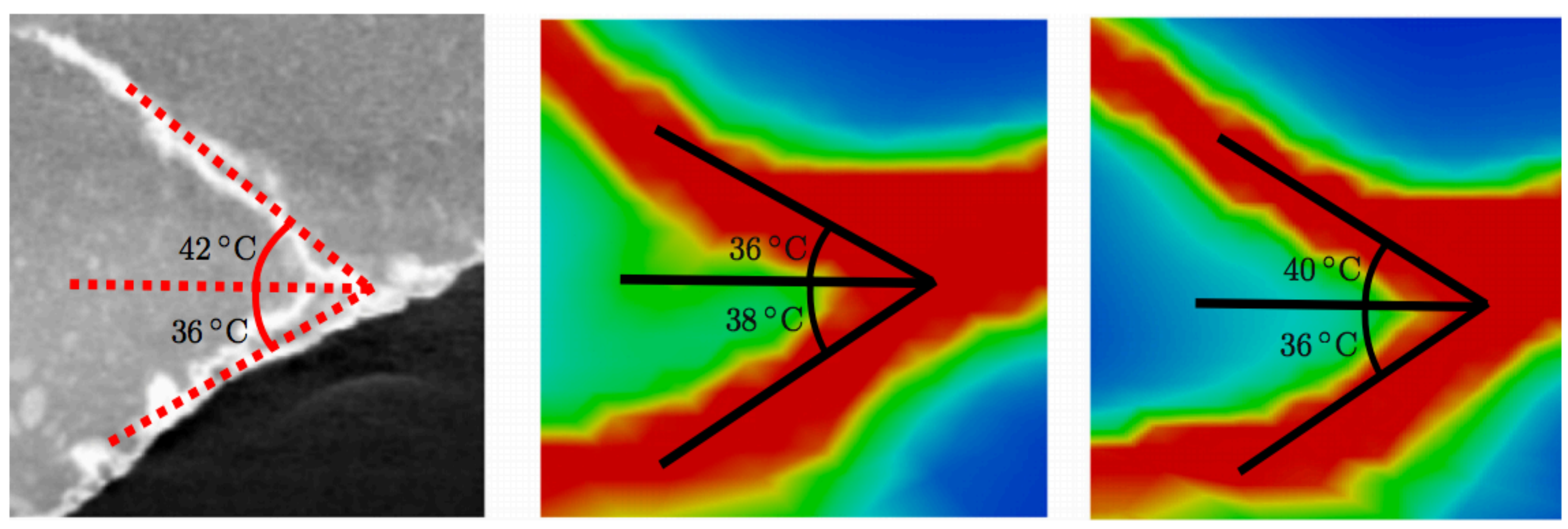


Fig. 4: Comparison of the crack branching angle between (left) the tomographic image in the interior of the specimen, (middle) the simulated results on face 1 and (right) the simulated results on face 2.

Conclusions

A remarkably good agreement between experimental and numerical results is found. This demonstrates the capability of the phase-field approach to predict complex mixed-mode fracture phenomena in cement mortar.

Reference

1: B. Bourdin G. A. Francfort, J. J. Marigo. Numerical experiments in revisited brittle fracture. *J Mech Phys Solids*, 48:797–826, 2000.

2: A. Carpiuc-Prisacari. Innovative tests for characterizing mixed-mode fracture of concrete: from pre-defined to interactive and hybrid tests, *Thesis*, ENS Cachan, 2015.

3: T. Wu et al. Phase-field simulation of interactive mixed-mode fracture tests on cement mortar with full-field displacement boundary conditions, *Eng Fract Mech,* 182: 658-688, 2017.